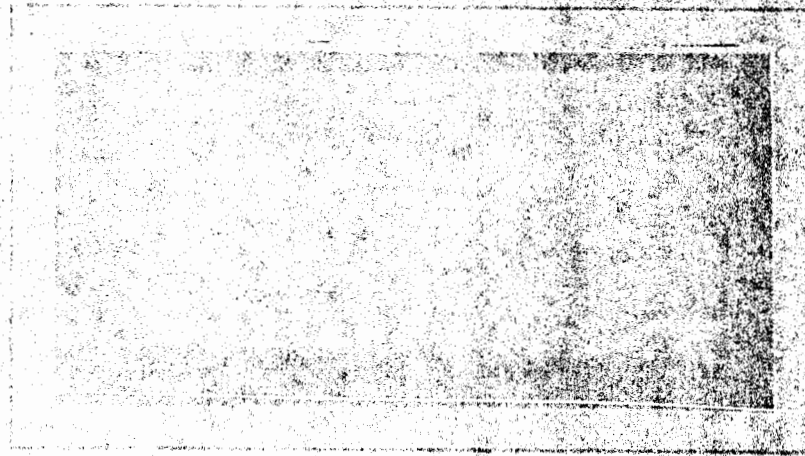① LEVEL

INSTITUTE OF TECHNOLOGY

AIR UNIVERSITY
UNITED STATES AIR FORCE

SCHOOL OF ENGINEERING

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

(1) LEVEL Ⅱ

AN INVESTIGATION ON THE INFLUENCE

OF STEP HEIGHT, FLOW STRAIGHTENING,

AND FLAMEHOLDERS ON DUMP COMBUSTOR

AFTERBURNER PERFORMANCE

THESIS

AFIT/GA/AA/78D-7   James A. Poier
                            Major   USAF

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AFIT/GA/AA/78D-7

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STEP HEIGHT, FLOW STRAIGHTENING, AND FLAMEHOLDERS

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air Training Command

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

James A. Poier, B.S.

Major   USAF

Graduate Astronautical Engineering

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Preface

This study is an effort to expand the continuing work
of optimizing a dump combustor type afterburner (A/B). This
afterburner, in combination with a small turbojet engine
derived from an automotive type turbocharger, is envisioned
as a low cost means of propulsion for Remotely Piloted
Vehicles (RPV). Specific areas of study include the effects
on performance of dump combustor step height changes, flow
straightening of the exhaust swirl at the turbine exit, and
the use of flameholders in conjunction with each configura-
tion. An estimate of afterburner thermal efficiency was
also made to aid in comparing the relative efficiency of
each modification. Determining optimum engine/afterburner
configuration for maximum performance remains the final
goal; perhaps this work has contributed another step to
that end.

I wish to express my thanks to Dr. William Elrod for
his time, effort, and suggestions as my thesis advisor. I
must also thank the entire staff of the AFIT Model Fabri-
cation Shop; Mr. Carl Shortt, Mr. Ron Ruley, Mr. Dave Grube,
Mr. Russel Murry, and Mr. John Brohas for not only superb
work, but cooperation above and beyond the call of duty.
Their combined efforts made this work a reality. Addition-
ally, I must extend my thanks to Mr. LeRoy Cannon and

Mr. John Parks who devoted considerable time and patience in making the test cell operational.

I also wish to thank Major Rami Dotan of the Israeli Air Force who shared the problems and long hours of this project as a part of his thesis requirement.

And finally, I must thank my wife, Louise, for her understanding and patience during the many hours spent away from home.

James A. Poier

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List of Symbols

Symbol		Quantity (Units)
Aug R	-	augmentation ratio
$\mathcal{R}$	-	aspect ratio (in.)
CPR	-	compressor pressure ratio
D	-	afterburner diameter (in.)
d	-	afterburner inlet diameter (in.)
F	-	corrected thrust (lb_f)
$\bar{F}$	-	uncorrected thrust (lb_f)
F_{sp}	-	specific thrust (lb_f-sec/lb_m)
FF_e	-	engine fuel flow (%)
FF_{ab}	-	afterburner fuel flow (%)
f_t	-	corrected fuel air ratio
$\bar{f}_t$	-	uncorrected fuel-air ratio
h	-	step height (in.)
Hr	-	hour
L	-	afterburner length (in.)
$\dot{m}_a$	-	corrected air mass flow (lb_m/sec)
$\bar{\dot{m}}_a$	-	uncorrected air mass flow (lb_m/sec)
$\bar{\dot{m}}_{ab}$	-	uncorrected afterburner fuel flow (lb_m/sec)
$\bar{\dot{m}}_{fe}$	-	uncorrected engine fuel flow (lb_m/sec)
$\bar{\dot{m}}_{ft}$	-	total uncorrected fuel flow (lb_m/sec)
$\dot{m}_{ft}$	-	total corrected fuel flow (lb_m/sec)

Symbol		Quantity (Units)
$\bar{N}$	-	uncorrected engine speed (rpm)
N	-	corrected engine speed (rpm)
P	-	pressure (psi)
P_t	-	total pressure (psi)
Δp	-	pressure differential (psi)
R	-	air gas constant (lb_f-ft/lb_m $^{\circ}$R)
SpGr	-	specific gravity
T	-	temperature ($^{\circ}$F)
T_t	-	total temperature (F)
ΔT	-	temperature differential (F)
TSFC	-	thrust specific fuel consumption (lb_m-Hr/lb_f)
θ	-	non-dimensional temperature correction factor
δ	-	non-dimensional pressure correction factor
η_T	-	augmenter thermal combustion efficiency (%)

Subscripts

a	-	air
A/B	-	afterburner
g	-	gage

Propulsion System Stations

0	-	ambient
3	-	compressor discharge
4	-	engine combustion chamber exit
5	-	turbine exit duct
6	-	A/B nozzle inlet

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Abstract

An investigation was made on the performance of a small turbojet/dump combustor afterburner combination as a function of varying afterburner step height, straightening of the exhaust flow swirl from the turbine exit, and installing flameholders of varying degrees of blockage. Results indicated that a step height of 0.5 inch provided the greatest increase in performance with respect to thrust, thrust specific fuel consumption, augmentation ratio, and specific thrust.

Performance was degraded in all cases when flow straighteners were used. Likewise, the addition of Y-shaped, V-gutter flameholders also degraded performance and in some cases made lighting the afterburner impossible. This result confirmed and expanded the data in reference 1. Comparing efficiencies tended to show decreasing efficiency with increasing step height.

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AN INVESTIGATION OF THE INFLUENCE OF
STEP HEIGHT, FLOW STRAIGHTENING, AND FLAMEHOLDERS
ON DUMP COMBUSTOR AFTERBURNER PERFORMANCE

I. Introduction

Background

A growing need for inexpensive remotely piloted
vehicle powerplants has led to an increasing amount of work
in converting automotive type turbochargers to turbojets.
Although successful as an operational concept; previous
test results have shown thrust levels less than desired.
To augment the engine thrust level, a sudden expansion
afterburner was proposed. Although thrust was increased
above non-afterburning levels, the optimum afterburner
performance was not established.

Wolfe (Ref. 10) and Barham (Ref. 1) provided basic
afterburner studies which demonstrated the feasibility of
the afterburner and showed that the optimum length-to-
diameter ratio (L/D) appeared to occur at values of both
three and five. An L/D=3 was later shown to be optimum by
Dotan (Ref. 4), even though engine/afterburner performance
was somewhat different from previous published results.

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Sudden Expansion Afterburners

A sudden expansion afterburner takes advantage of the recirculation zone created when the engine exit duct cross-sectional area is suddenly changed to a larger value. The recirculation zone created by this expansion is a very complex flow field which, among other things, provides good turbulent mixing of unburned air and newly injected fuel (Fig. 1). Additionally, it acts as a stable flameholding region which requires no other mechanical flameholders to operate.

Afterburner length must be sufficient to contain the combustion process, however, past results indicate that any substantial length beyond that appears to contribute only size, weight, and at best, similar performance (Refs. 1, 4).

Objective

The objectives of this study were:

1. Determine what effect changing dump combustor step height (h) has on performance.

2. Determine whether straightening the swirling flow field coming from the engine exit duct provides any increase in performance.

3. Determine if mechanical flameholders are of value when used with different step heights.

4. Make preliminary afterburner efficiency

Fuel Injection

Imbeded
Vortices

Flow Recirculation

Flow Reattachment

A

D

h

L

A

A/B Duct

Turbine Exit
Duct

A/B Inlet
Swirl

Turbine Exit
Swirl

Section A-A
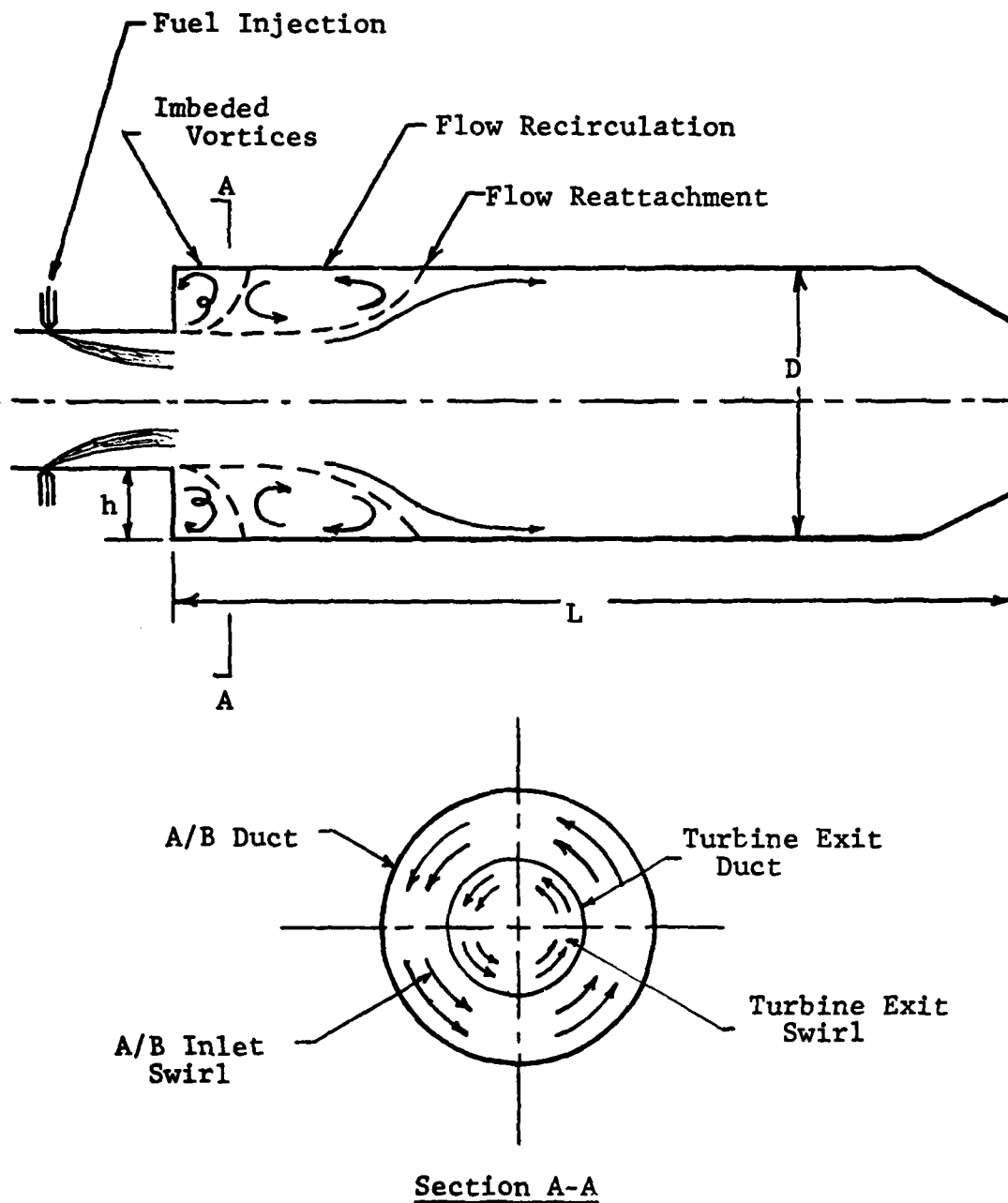
Fig. 1   Sudden-Expansion Combustor Flowfield

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calculations based on adiabatic flame temperature and measured values of turbine exit and afterburner exit temperatures.

Scope

This study focuses on changes in dump combustor step height and the effect it has on the recirculation zone and overall engine/afterburner performance. Step heights used were 1.25, 1.0, 0.75, and 0.5 inches. The afterburner length-to-diameter ratio chosen was three, based on results by Dotan (Ref. 4).

The use of baffles to straighten the turbine exit flow prior to the expansion region was investigated to determine if reducing the swirl to the combustor provides better mixing and combustion. These baffles were used with the 1.0, 0.75, and 0.5 inch step height configurations.

Flameholders similar to those used by Barham were run at various step heights, providing blockages of 5, 10, and 15 per cent. A circular flameholder, with a blockage of 25%, was also run as a preliminary investigation.

Turbine inlet temperature was held at 1700F for all runs to enhance turbine blade life and provide a safety factor in the event the afterburner nozzle failed to eject during afterburner initiation. Two engine configurations were used for comparison purposes, one providing a low mass flow (turbine AR=1.7) and the other a high mass flow (turbine AR=1.5). The afterburner is protected from

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3000F temperatures by water cooling. Afterburner exit
diameter during operation was held constant at 4.0 inches
for all test runs.

The remainder of this report covers the test equipment
used in the investigation, procedures used in determining
the experimental data, results obtained, and finally the
conclusions and recommendations drawn from this data.

II. Test Apparatus

General Description

The basic engine is fabricated from an AiResearch
T18A-E turbocharger to which a modified MA-1A air starting
unit combustor was added. Compressor housing aspect ratio
was 0.96, while two different turbine housing aspect ratios
of 1.5 and 1.7 were used to provide both high and low air
flow rates. Aspect ratio is defined as the ratio of the
housing inlet throat area to the radial distance from the
centroid of this area to the center of the turbine wheel
(Ref. 7).

The afterburner section used for all tests had a
length-to-diameter ratio of three (Fig. 2). An ejectable
nozzle was used to control the back pressure rise during
afterburner light off. This two stage nozzle provided an
exit diameter change from 3.25 inches for the complete
assembly, to 4.0 inches when ejected. The nozzle is
described in detail in Ref. 10. A schematic drawing of the
engine/afterburner combination is shown in Fig. 3.

Step Height Diffusers

Changes in step height were accomplished with inter-
changeable diffuser sections mounted between the engine
exit and the afterburner entrance. See Fig. 4 for the gen-
eral diffuser shape and overall dimensions of each diffuser.
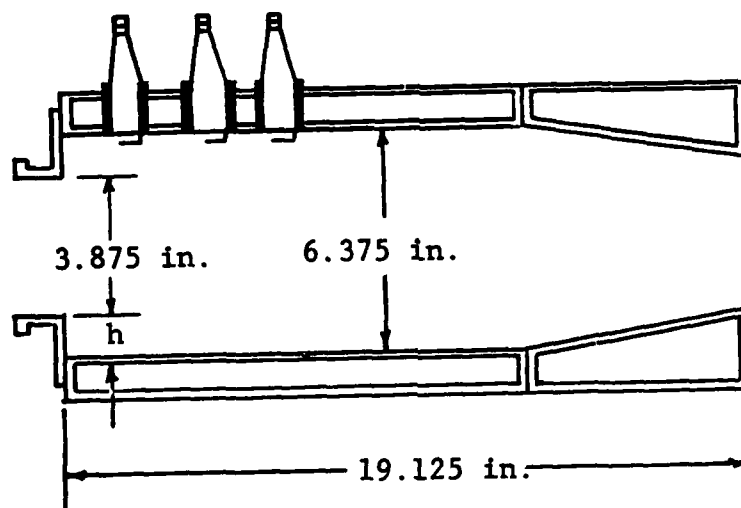
Fig. 2 Dump Combustor, L/D=3
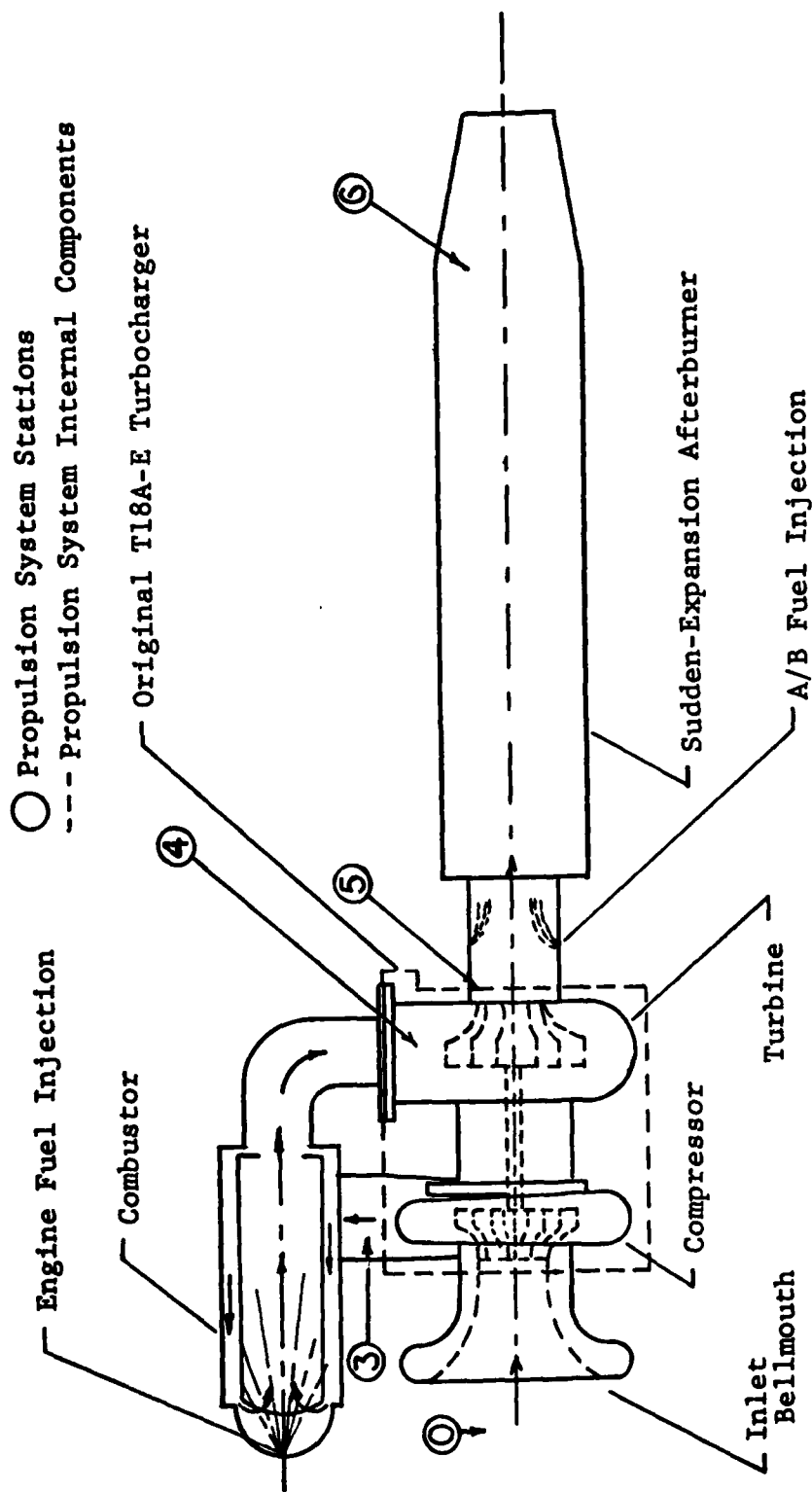
Fig. 3 Test Apparatus Schematic

○ Propulsion System Stations
--- Propulsion System Internal Components

Original T18A-E Turbocharger

Sudden-Expansion Afterburner

A/B Fuel Injection

Engine Fuel Injection

Combustor

Turbine

Compressor

Inlet Bellmouth

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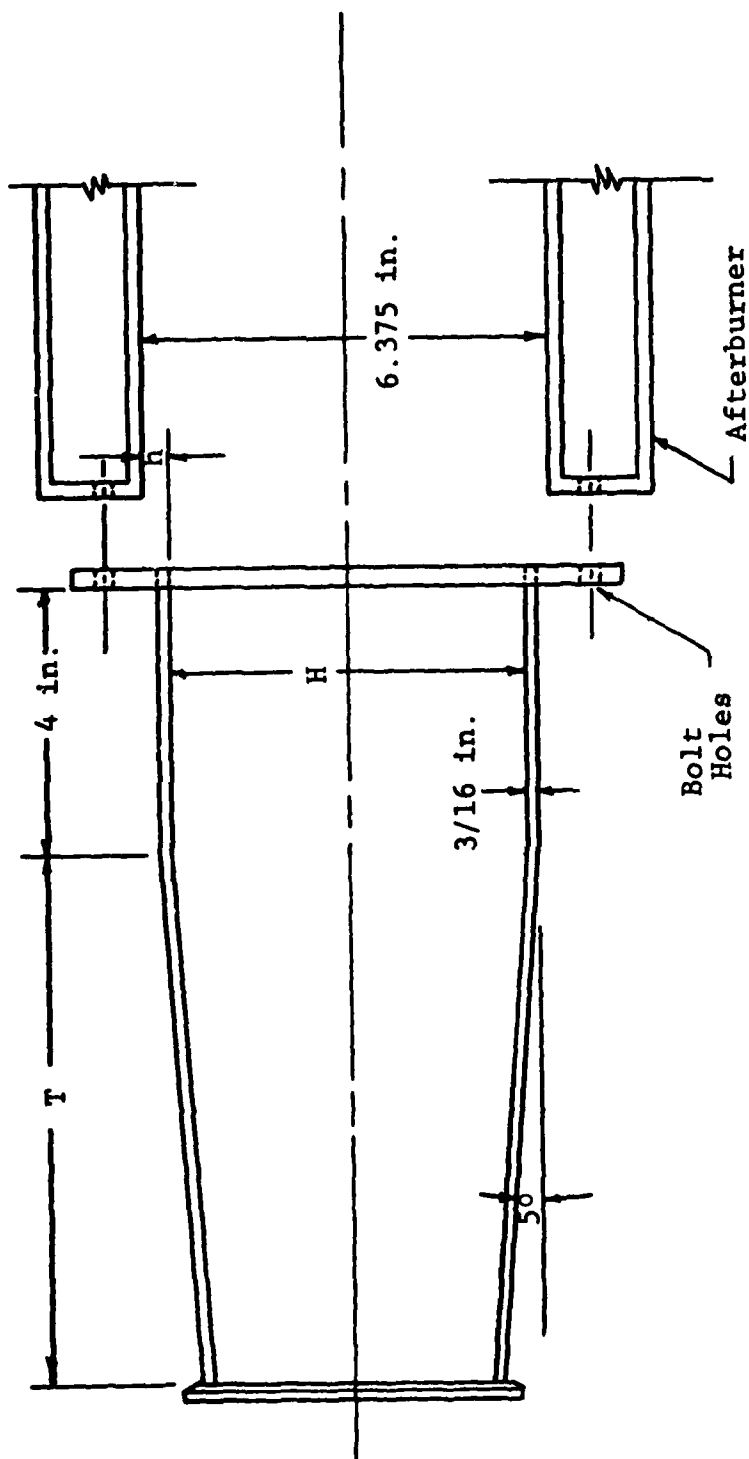
Fig. 4 Step Height Diffusers

h-in.	H-in.	T-in.
0.5	5.375	8.573
0.75	4.875	5.715
1.0	4.375	2.858

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The value of the diffusion half angle for all three
sections was held constant at five degrees to guard against
flow separation during expansion. This value was chosen
using Ref. 6 as a guide. Each section was held in place by
Marmon clamps at the turbine exit and six evenly spaced
bolts at the afterburner entrance.

Flow Straightening Baffles

A baffle for each diffuser was fabricated in a cross
pattern and welded to a ring which mounted between the
diffuser and the afterburner (See Fig. 5). This section
was inserted into the diffuser and held in place by the
same bolts which hold the diffuser. Each straightener
provided a nominal area blockage of 3.6 percent.

Flameholders

Three flameholders were fabricated for each diffuser
section and mounted at the afterburner step. The configu-
ration used was geometrically similar to those described by
Barham in Ref. 1. Blockages of 5, 10, and 15 percent were
used. Figure 6 may be referred to for the shape and dimen-
sions used during the testing.

A circular flameholder, machined from stainless steel
stock, is shown in Fig. 7. This flameholder created a 25
percent area blockage and was used with the 0.75 inch step
height diffuser. The purpose of this flameholder was to

H

1/16 in.

4 in.
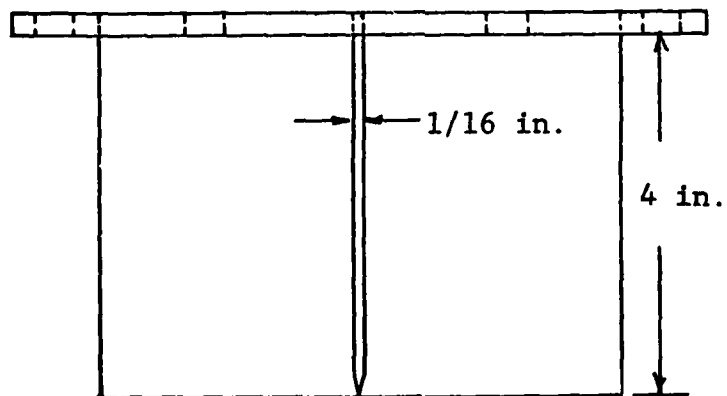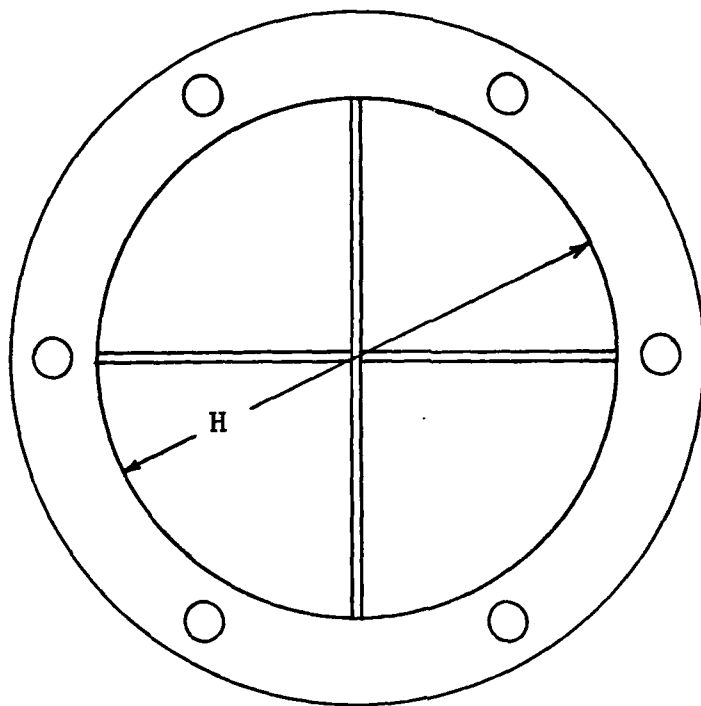
Note: H values same as Fig. 4

Fig. 5 Flow Straighteners

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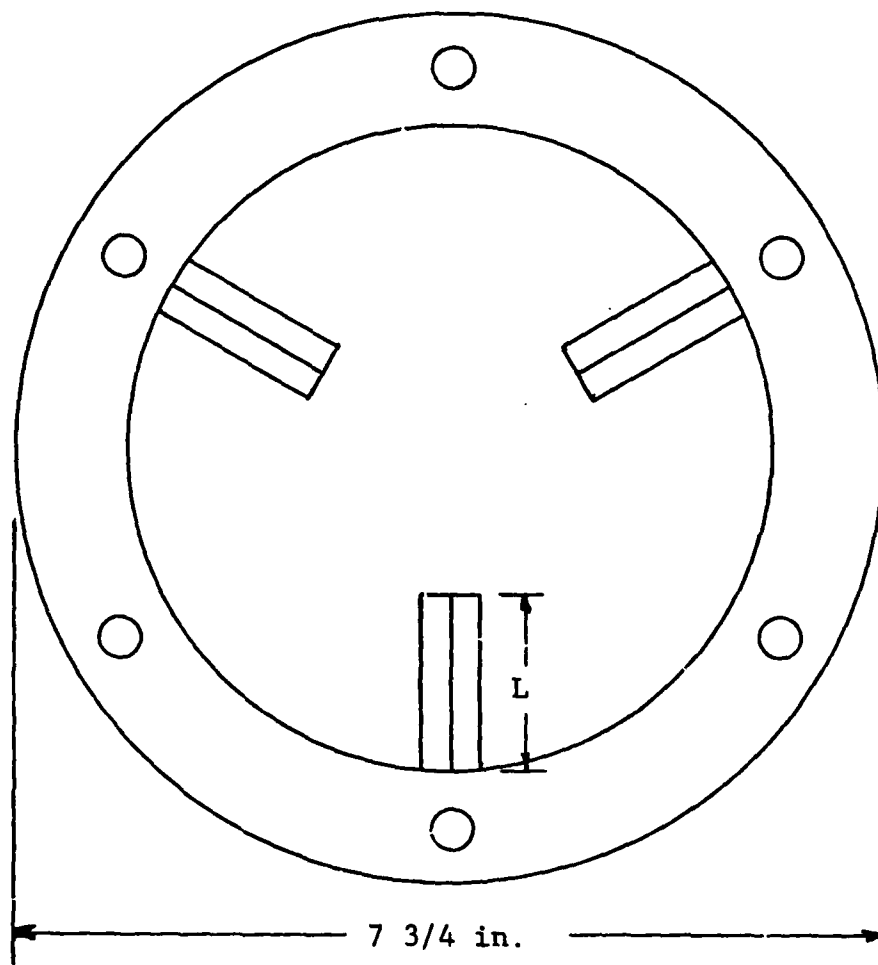
Flameholder Length (L)-in.			
h-in.	Blockage-%		
	5	10	15
0.5	1.008	2.017	3.025
0.75	0.83	1.659	2.489
1.0	0.668	1.336	2.004

Fig. 6   Y-Shaped, V-Gutter Flameholders

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7 3/4 in.

4.875 in.

1/4 in.

Note: Blockage=25%

3/8 in. 60°
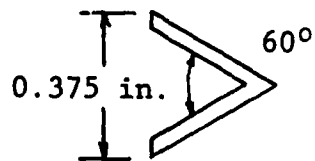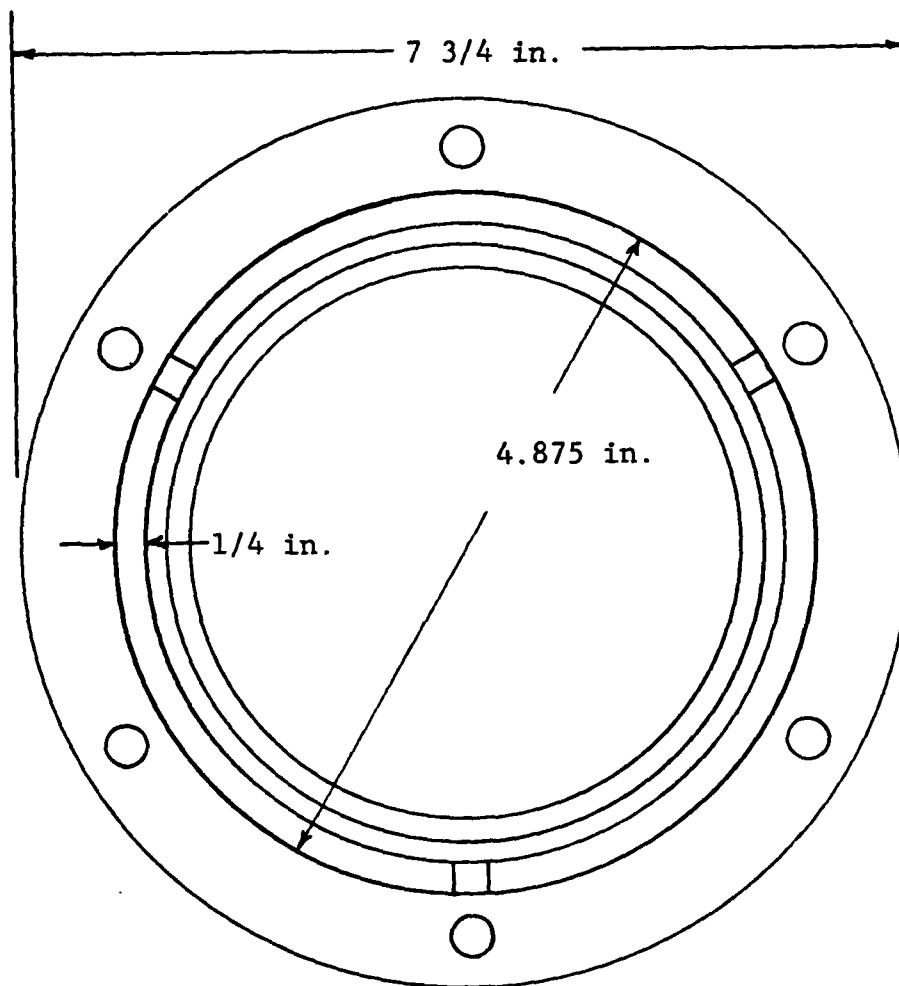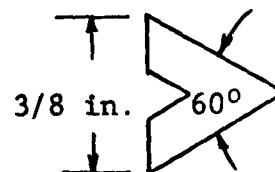
Fig. 7 Circular Flameholder

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determine if an annular shape is better adapted to the swirling exhaust flow pattern and hence, show promise of better performance.

Instrumentation

Engine pressures (P_3, P_4, P_5, and P_{t5}) were measured by using pressure transducers and recorded on a Honeywell 906B Visicorder. Afterburner nozzle inlet pressure (P_{t6}) was measured by a direct reading pressure gage located in the control room. Refer to Fig. 3 for pressure and temperature probe locations.

Engine temperature (T_3, T_{t4}, and T_{t5}) and afterburner nozzle temperature (T_{t6}) were measured using bare wire thermocouples. Temperatures T_3 and T_{t6} were recorded on the Honeywell Visicorder while T_{t4} and T_{t5} were recorded manually from direct reading gages.

Engine thrust was measured using a strain gage mounted on a flexure piece and recorded directly on the Honeywell Visicorder. Engine rpm was measured by a light sensitive photodiode device which provided a frequency reading on a digital counter proportional to rpm. This reading was manually recorded and converted to rpm. Engine and after-burner fuel flow was recorded on a Honeywell Chart Recorder Model SY153X(28) using electrical signals generated by turbine flow meters inserted into each of the fuel lines. Finally, air mass flow to the engine was determined by manually recording the water level of a water manometer

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and then converting inches of water to pounds mass flow per second using a calibrated Bellmouth inlet (Ref. 5).

Ambient air temperature (T_o) was recorded from a free standing thermometer located on the test stand directly in front of the engine intake. Ambient air pressure (P_o) was recorded from a mercury manometer located inside the test cell control room. Fuel specific gravity was measured by a hydrometer lowered into a sample of fuel taken from the main fuel line prior to each engine run. All test cell instrumentation were calibrated before the experimental program started.

Measurement Accuracies

The accuracy of each individual measurement is estimated according to the following:

1. Pressure (gage) - ±0.2 psi

2. Pressure (Visicorder) - ±0.1 psi

3. Low Range Temperatures - ±5F (Visicorder)
   (0-400F)

4. High Range Temperatures - ±40F (Visicorder);
   (1150-3200F)   ±20F (Gage)

5. RPM - ±150

6. Thrust - ±1 lb_f

7. Fuel Flow - ±10^{-4} lb_m/sec

8. Air Mass Flow - ±0.05 lb_m/sec

9. Ambient Pressure - ±0.01 in Hg

10. Ambient Temperature - ±1F

11. Fuel Specific Gravity - ±0.005

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III. Testing Procedure

Previous investigations of ramjet dump combustors
concluded that step height is an important parameter when
length-to-diameter ratio is less than five (Ref. 3). Work
by Dotan showed that for the dump combustor afterburner
being studied for possible RPV application, an L/D of 3 was
optimum (Ref 4). This investigation then, centers around
system performance when changes in step height are made at
a constant L/D of 3. Performance was also examined when
turbine exhaust flow straighteners and mechanical flame-
holders were inserted into the flow.

Step height was varied by fabricating three diffusers
which provided values of 1.0, 0.75, and 0.5 inches. These,
combined with the original step height of 1.25 inches, were
the four values used in this investigation. A separate
flow straightener and three Y-shaped flameholders (providing
5, 10, and 15 percent blockage) were also used with each
diffuser.

Since both the flow straighteners and the flameholders
degraded overall system performance, consideration was
given to building a device which was more compatible with
the swirling exhaust flow. Accordingly, a preliminary
investigation was made using a circular flameholder
attached to the 0.75 inch step height diffuser.

The actual running procedure used was identical for all test configurations. Also, many configurations were run more than once to insure repeatibility of data.

Basically, the engine was started, warmed up, and the throttle advanced until the turbine inlet temperature (T_{t4}) reached 1700F (defined as MIL 1). The engine was allowed to stabilize at this setting before recording MIL 1 data points. Following this, the afterburner was ignited and the engine retrimmed to 1700F. This condition provided the second data point.

Additional data points were obtained by increasing A/B fuel flow in increments of 10% until reaching 100%. At each data point, turbine inlet temperature was retrimmed to maintain 1700F. At the conclusion of the afterburner run, the A/B fuel flow was cut off and the turbine inlet temperature reset to 1700F. The final data point (MIL 2) was recorded with the ejectable nozzle removed.

IV. Experimental Results

The data presented here resulted from testing different afterburner step heights, flow straighteners, and flame-holders. Two runs of identical configuration were made when possible to insure repeatibility of data. An L/D of 3 was used as a basic configuration on which each of the features was investigated. Data points in the graphical presentation of results are connected by straight lines for the purpose of clarity and not to indicate measured parameter performance between the points.

Effects of Afterburner Step Height Changes

Step height (h) changes were studied on two different engine configurations, one which provided a low mass flow condition (AR=1.7, Eng A) and the other a high mass flow (AR=1.5, Eng B). Results were consistent between the two configurations. Also, calculation of Augmentation Ratio was important to this study and is defined as the after-burner thrust level divided by the thrust at MIL 1 conditions. Maximum Augmentation Ratio is simply the maximum thrust developed by the A/B during the run divided by MIL 1 thrust.

As shown in Fig. 8, the maximum augmentation ratio decreased with increasing step height over the range studied. For engine B, the total augmentation ratio

18
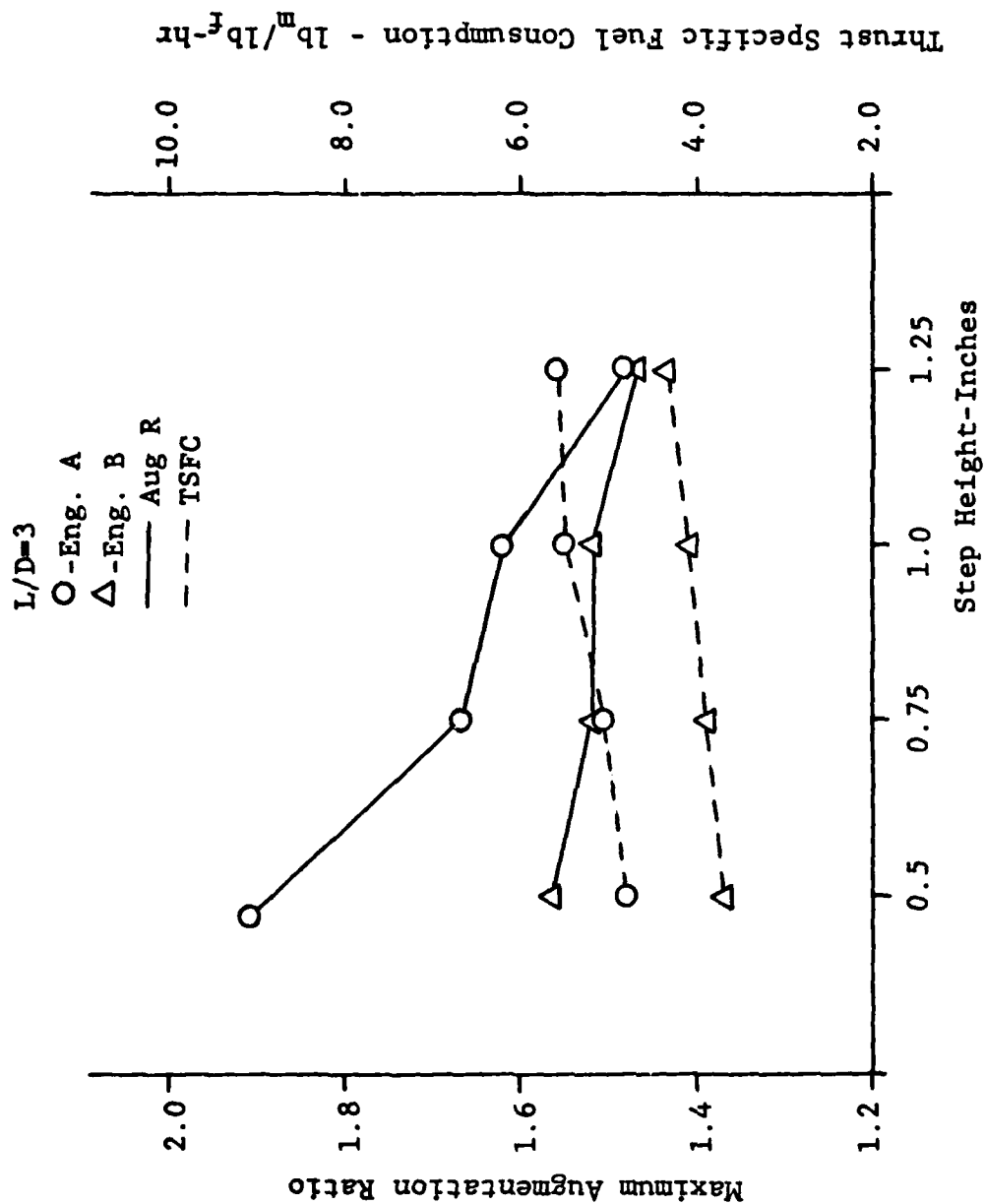
Fig. 8 Effect of Step Height on Maximum Augmentation Ratio and Thrust Specific Fuel Consumption

decrease was only 5.9% over the step height range, while for engine A the change was a much larger 22.5%. Since the augmentation ratio is virtually equal for both engines with h=1.25 inches, the plot indicates that smaller step heights are more effective for the lower mass flow situation. This appears to be due to a greater diffusion effect on the turbine exit flow for engine A. The smaller step heights have the longest diffuser sections, thus allowing for better fuel vaporization and combustion. At the large step heights, fuel-to-air ratio is over stoichiometric and then converges to stoichiometric conditions at the smallest step height. This provides a steady increase in A/B temperature, thermal efficiency, and augmentation ratio for engine A as step height is reduced (See Figs. 9 and 16). Engine B operates at or near stoichiometric conditions for all step heights, hence, less performance change. See reference 9 for a discussion of diffusion effect on fuel vaporization and combustion.

The same figure also plots TSFC versus h. Here the trend is almost identical for the two engines, with each showing a 14% increase in TSFC as h is increased. It also clearly shows the high mass flow engine operating at lower TSFC's across the range. This is because when operating at a given fuel flow rate, stoichiometric conditions provide greater thrust, hence lower TSFC, than when operating at fuel rich conditions.

Figure 9 compares the change in maximum augmentation ratio with the associated A/B nozzle temperature (T_{t6}). Differences in the two engines are apparent from the recorded temperatures. As mentioned previously, engine A operates in an over rich condition at the larger step heights and then converges to stoichiometric at h=0.5 inch, giving the rise in T_{t6} as step height decreases. Engine B operates at or near stoichiometric for all step heights and the graph reflects the small fluctuations in fuel/air ratio.

Figures 10 and 11 show the augmentation ratio plotted for each step height over the fuel flow range of the afterburner. Only a slight increase or variation was noted. The average difference between minimum and maximum values for engine A was only 5.9%, while for engine B it increased slightly to 9.8%.

Since the augmentation ratio curves were quite flat, thrust was plotted versus fuel/air ratio for comparison with past results (Ref. 1). Figure 12 shows much flatter thrust curves then those shown in earlier work. Test data shows that increasing A/B fuel flow increases T_{t6}, however, there is also an accompanying drop in engine air mass flow which leads to virtually constant thrust throughout the A/B range. This process is more prevalent in the low mass flow case than in the high case. Previous results showed thrust increases up to 20% with increasing fuel flow, whereas these test results show a maximum increase of 14%

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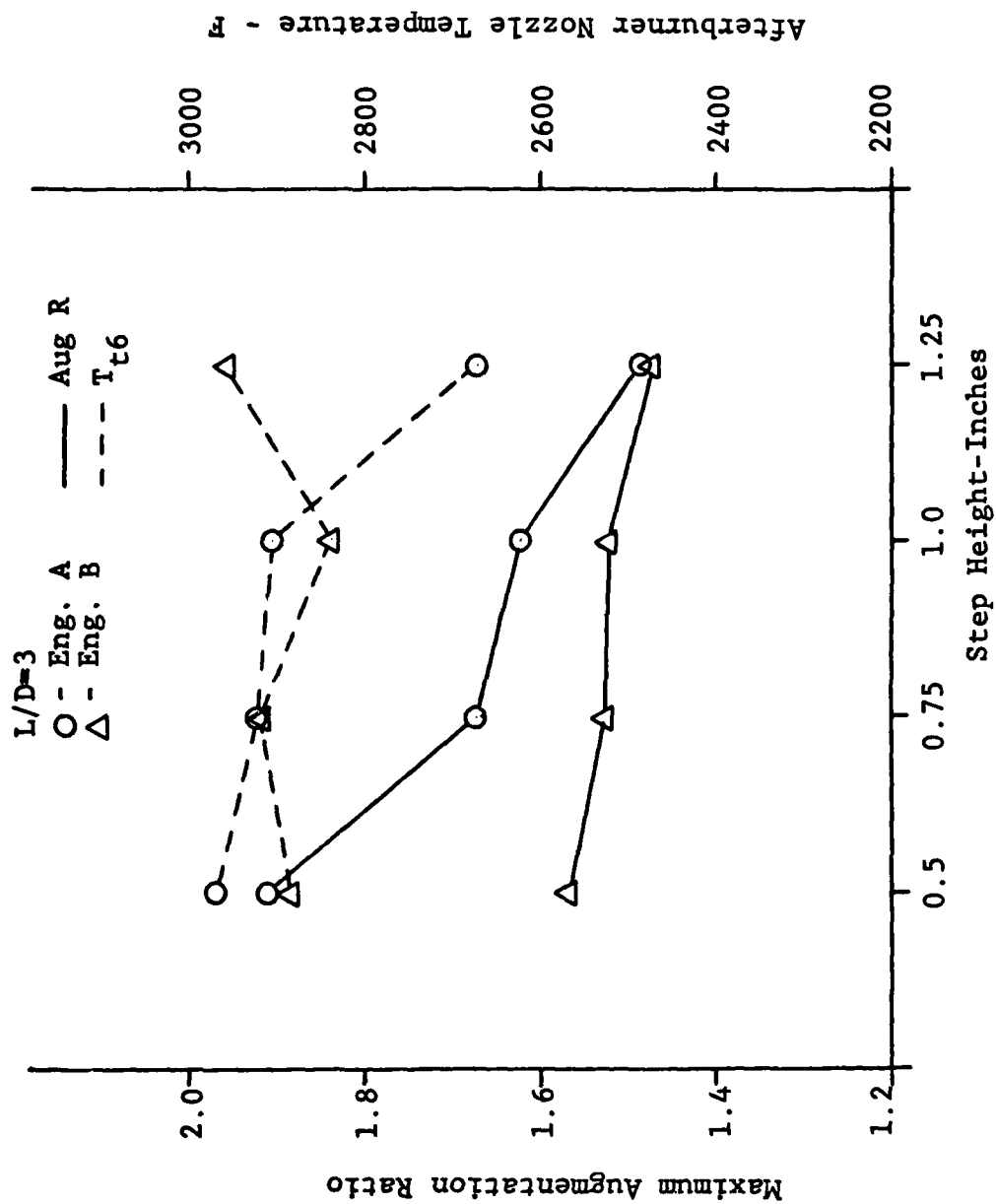
Fig. 9 Effect of Step Height on Maximum Augmentation Ratio and Afterburner Nozzle Temperature (T_{t6})

22
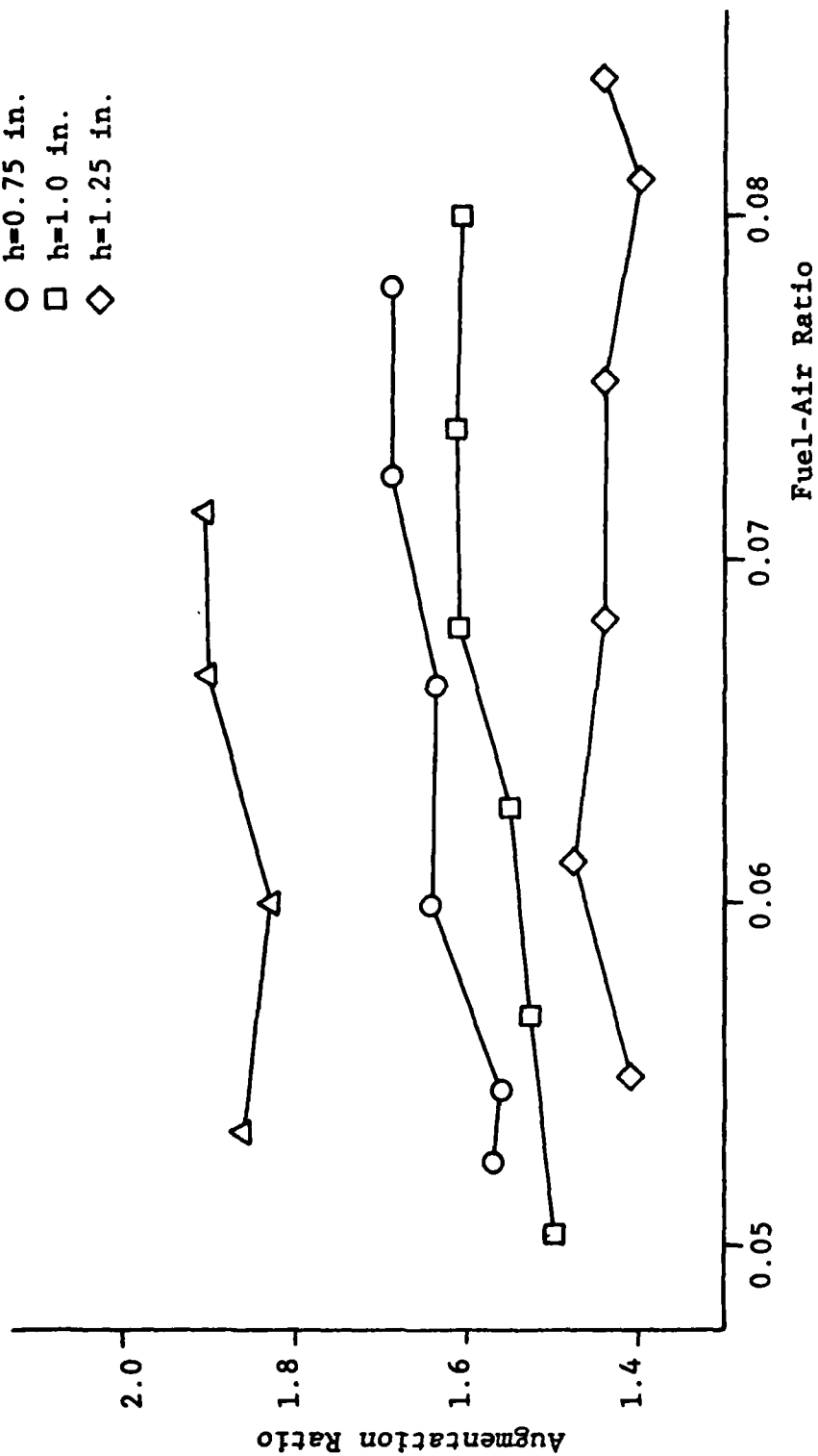
Fig. 10 Effect of Fuel-Air Ratio Changes on Augmentation Ratio,
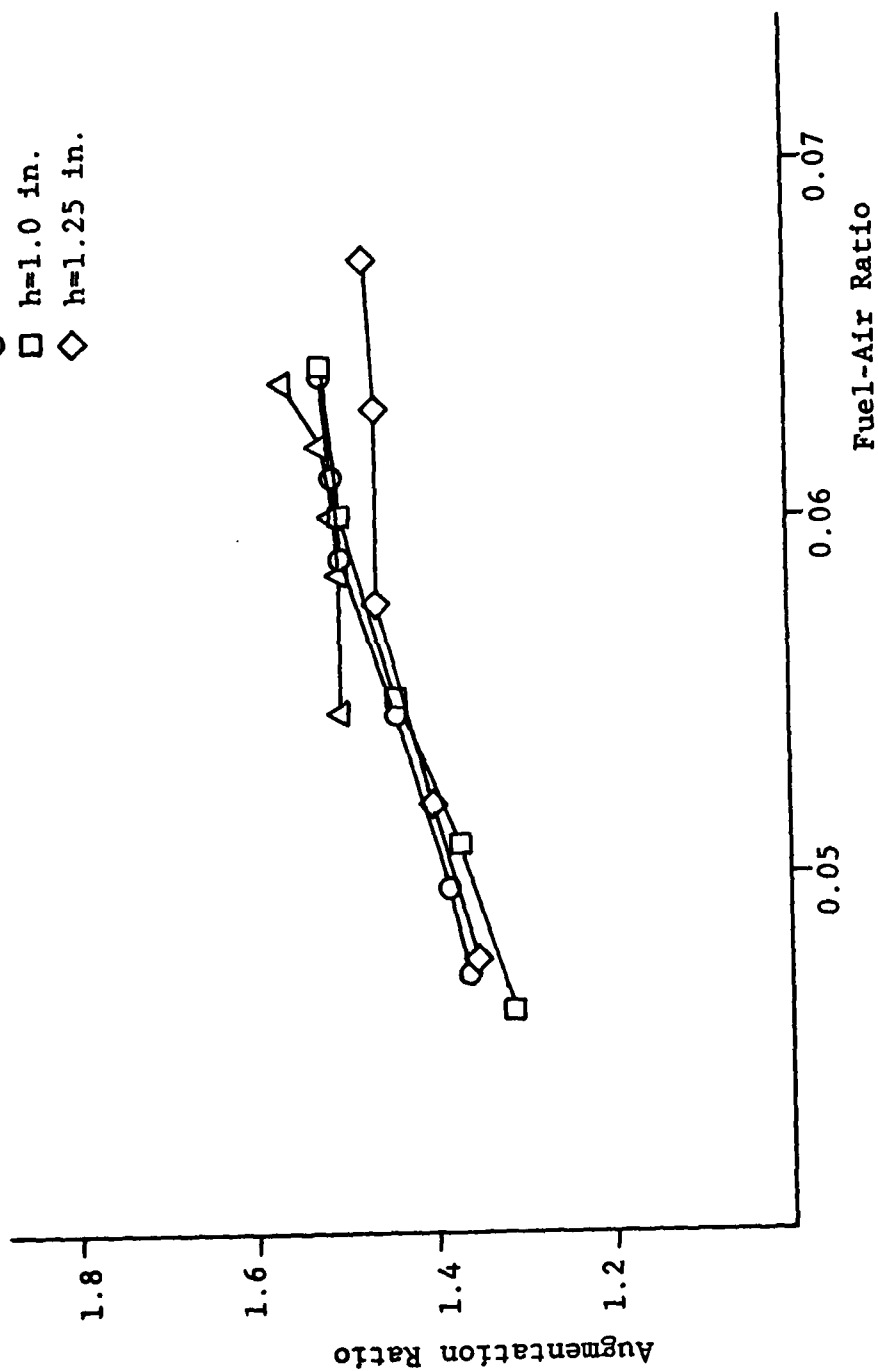Engine A

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Fig. 11 Effect of Fuel-Air Ratio Changes on Augmentation Ratio, Engine B

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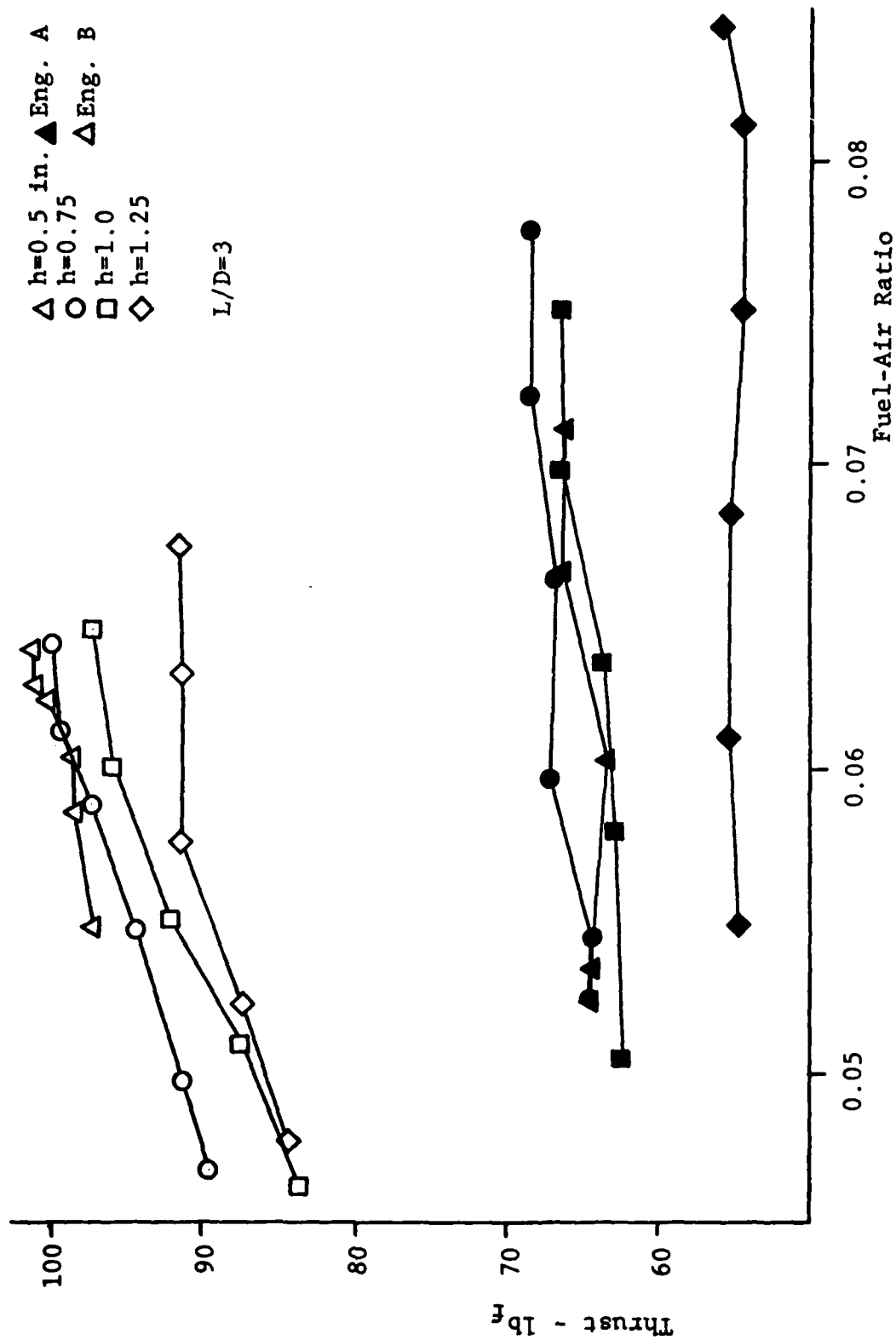
Fig. 12 Effect of Fuel-Air Ratio Changes on Thrust, Engines A and B

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in the extreme case, with the average change being only 7%. Also of interest, is the fact that, to achieve a 14% change in thrust requires a 28% increase in fuel flow while at the same time lowering the overall thermal efficiency by 3% and increasing TSFC by 16 %. Specific thrust increases approximately 18%. This then would suggest an on-off operation of the afterburner. This would lead to a less complicated fuel control and lower acquisition/maintenance costs.

Figures 13 and 14 plot specific thrust (F_{sp}) versus TSFC which may be used to provide insight into what configurations give best thrust. Again, the trend is to smaller step heights which clearly give greater thrust per pound of air at lower fuel consumption rates.

Afterburner pressure losses are graphically presented in Fig. 15. Maximum augmentation ratio is also plotted for comparison purposes. A similar pattern occurs for both low and high flow engines which shows pressure losses approximately equal for the smaller step heights and then gradually increasing as step height increases. The fact that the total pressure drop increases as augmentation ratio decreases is probably due to higher entrance mach numbers as step height is increased (less flow diffusion) and also the lower mass flow condition which results as step height was increased.

An estimate of combustor thermal efficiency (η_T) was used to see how efficiency varies according to step height. Here, the emphasis was on the relative efficiency changes,

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Fig. 13 Specific Thrust vs. Thrust Specific Fuel Consumption, Engine A

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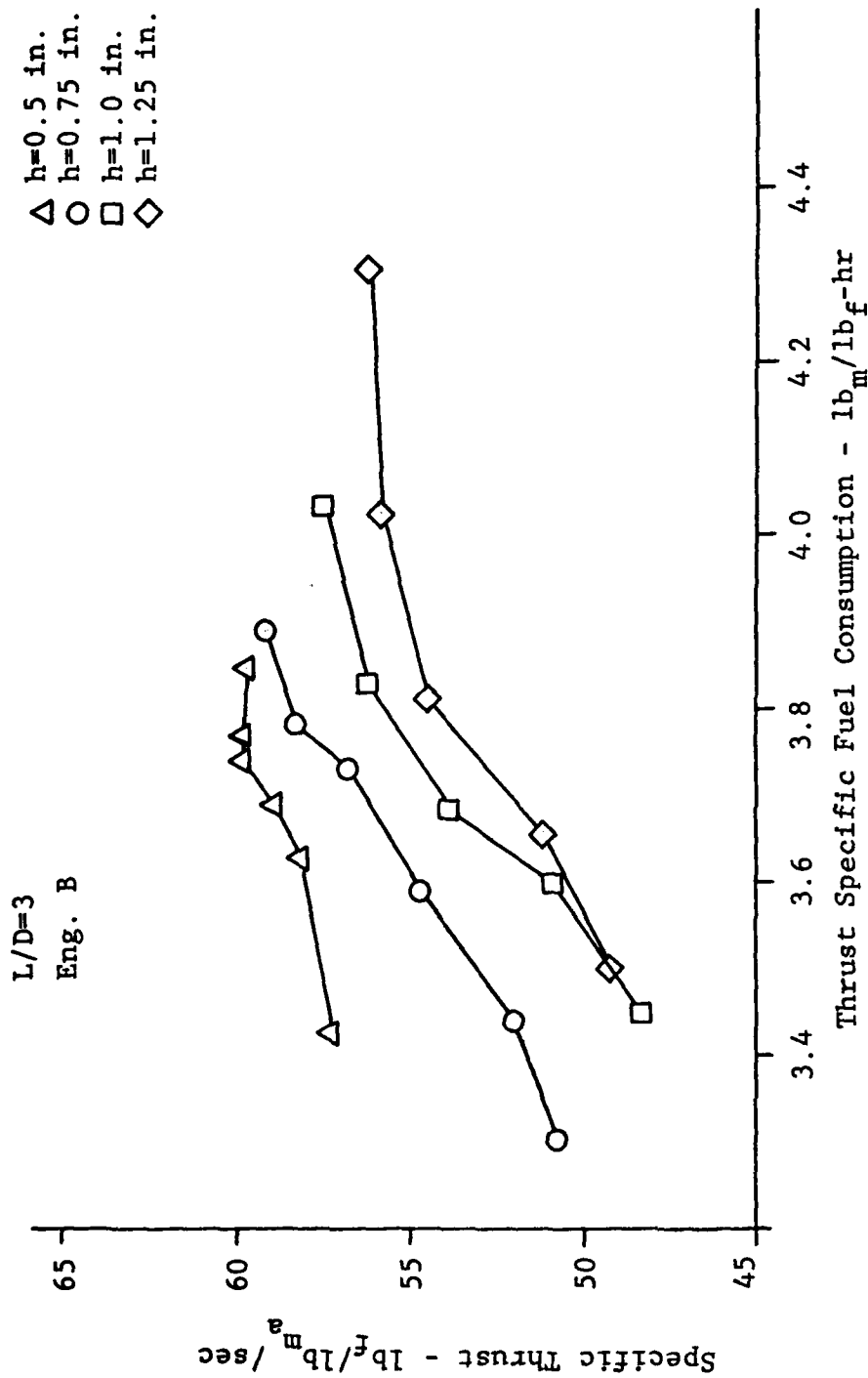
Fig. 14 Specific Thrust vs. Thrust Specific Fuel Consumption, Engine B
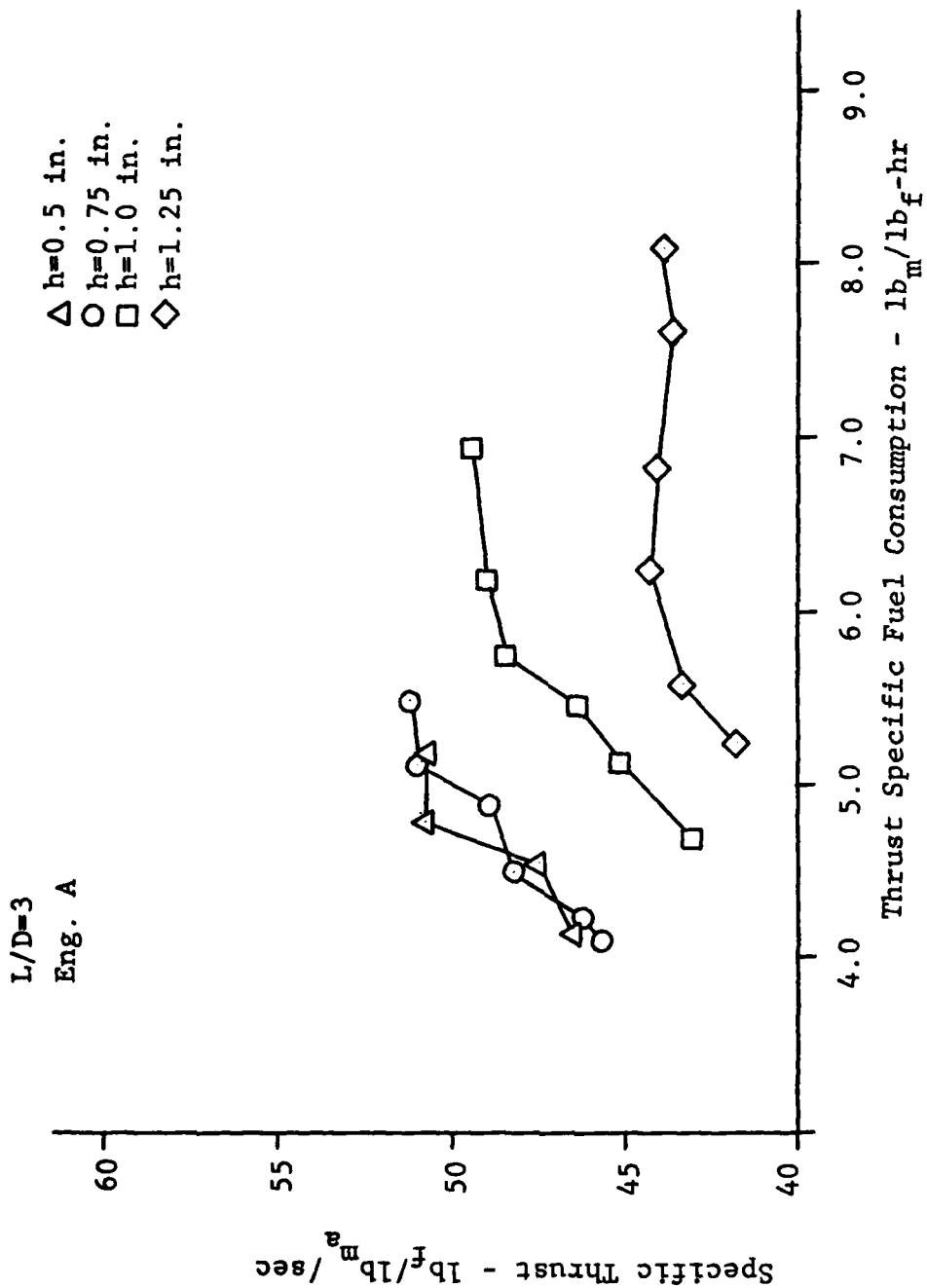
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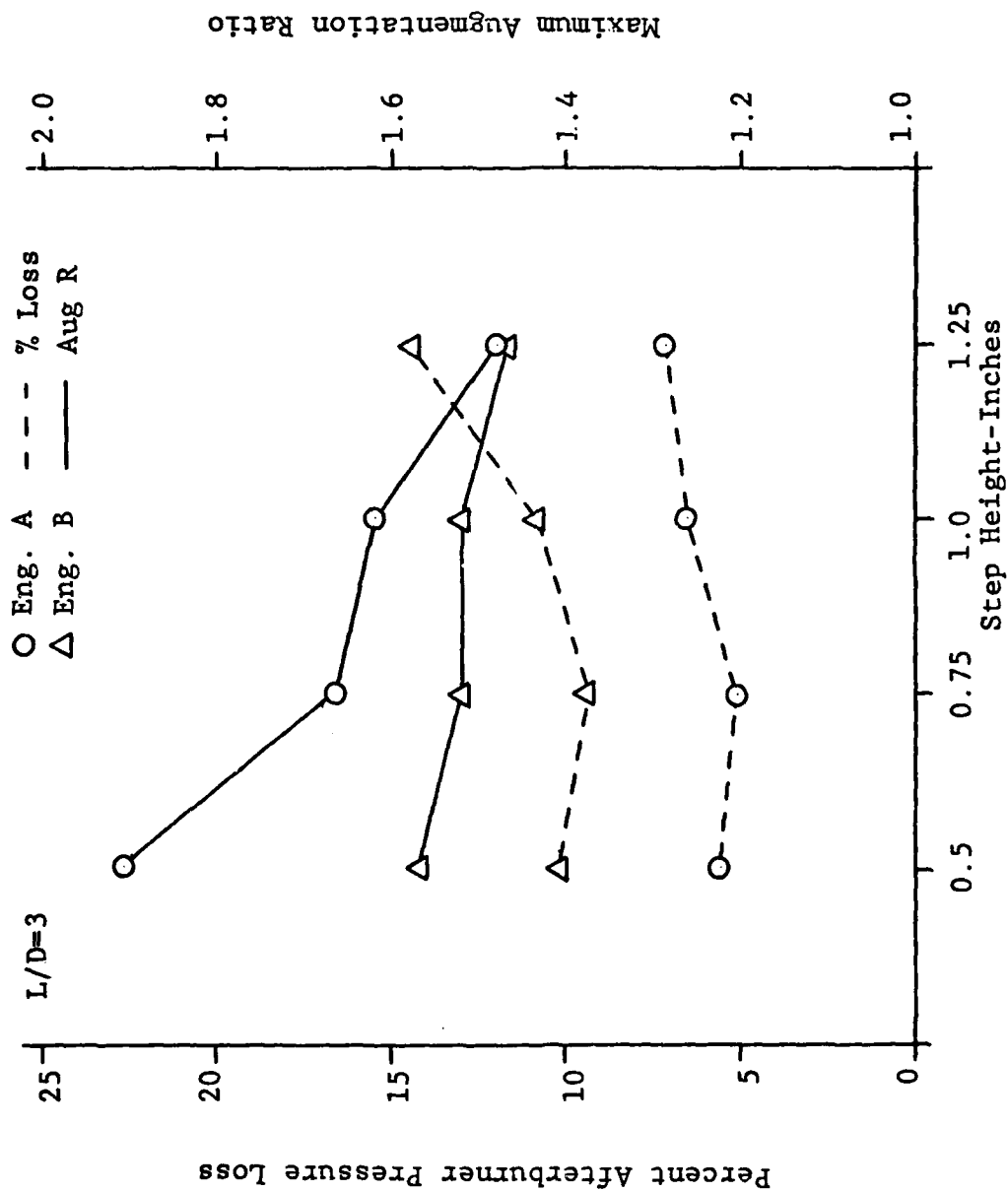
Fig. 15 Effect of Step Height Changes on Afterburner Pressure Losses

not the absolute efficiency value. The results are shown in Fig. 16. Again, the smaller step heights appear more efficient, the notable exception being the value plotted for engine B at h=1.25 inches. Here, it is possible a change in flow pattern has occurred which provides improved mixing with a resulting higher T_{t6}.

The step height study points out the sensitivity of engine A/B performance to the complex flow field which occurs at and downstream of the step and its interaction with engine flow, heat release, and pressure loss. The details of this flow field are essentially unknown at this time, which suggests a comprehensive investigation into determining exactly what the description of the recirculation zone is, and what effect it has on fuel addition, heat release, pressure loss and mass flow. This would be very helpful in analyzing performance trends.

Effects of Flow Straightening

Baffles were inserted into each diffuser in an attempt to straighten the engine exhaust flow. The results consistently showed decreased performance (with one exception) over the same configuration without straighteners. Figures 17, 18, and 19 are typical of the results obtained. The blockage ratio which resulted from placing the straighteners in the flow was 3.6%. The one exception mentioned was a decrease in TSFC with decreasing maximum augmentation ratio; opposite to plots without straighteners. This is due to a

Fig. 16 Effect of Step Height on Afterburner Efficiency

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Fig. 17   Effect of Step Height Changes on Maximum Augmentation Ratio and TSFC With and Without Flow Straighteners

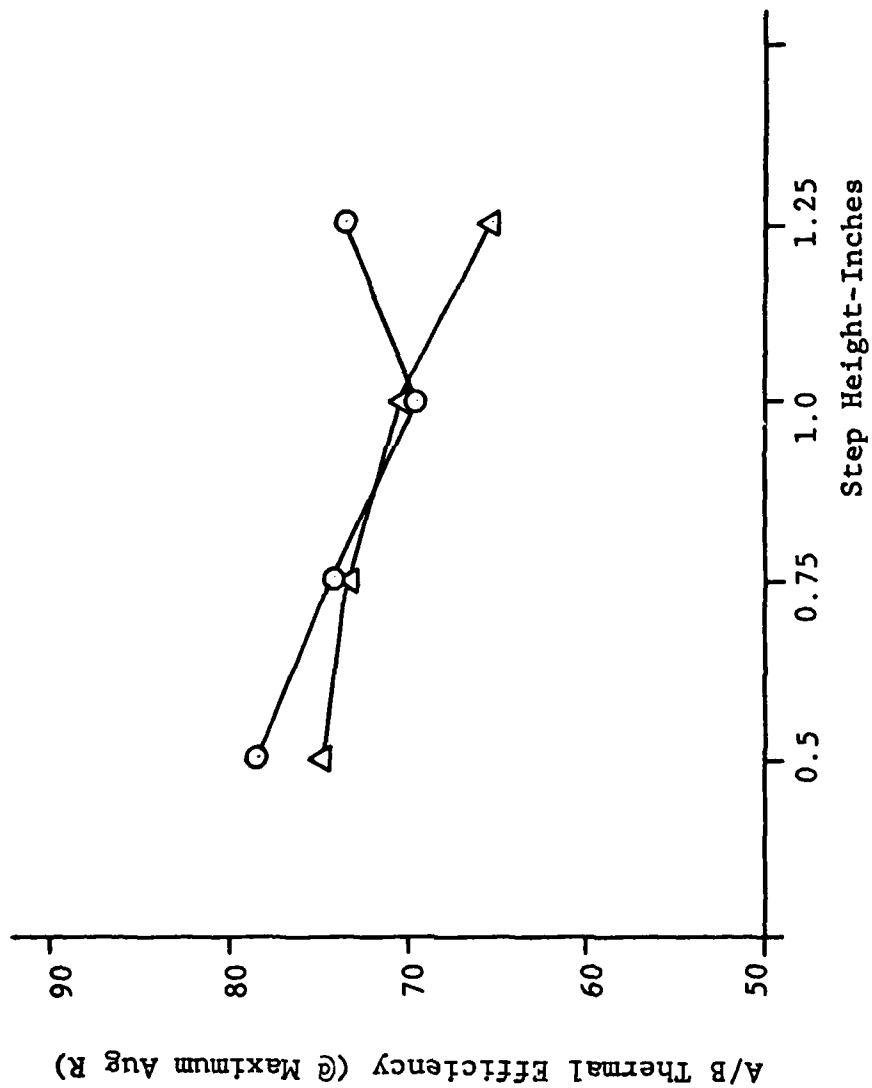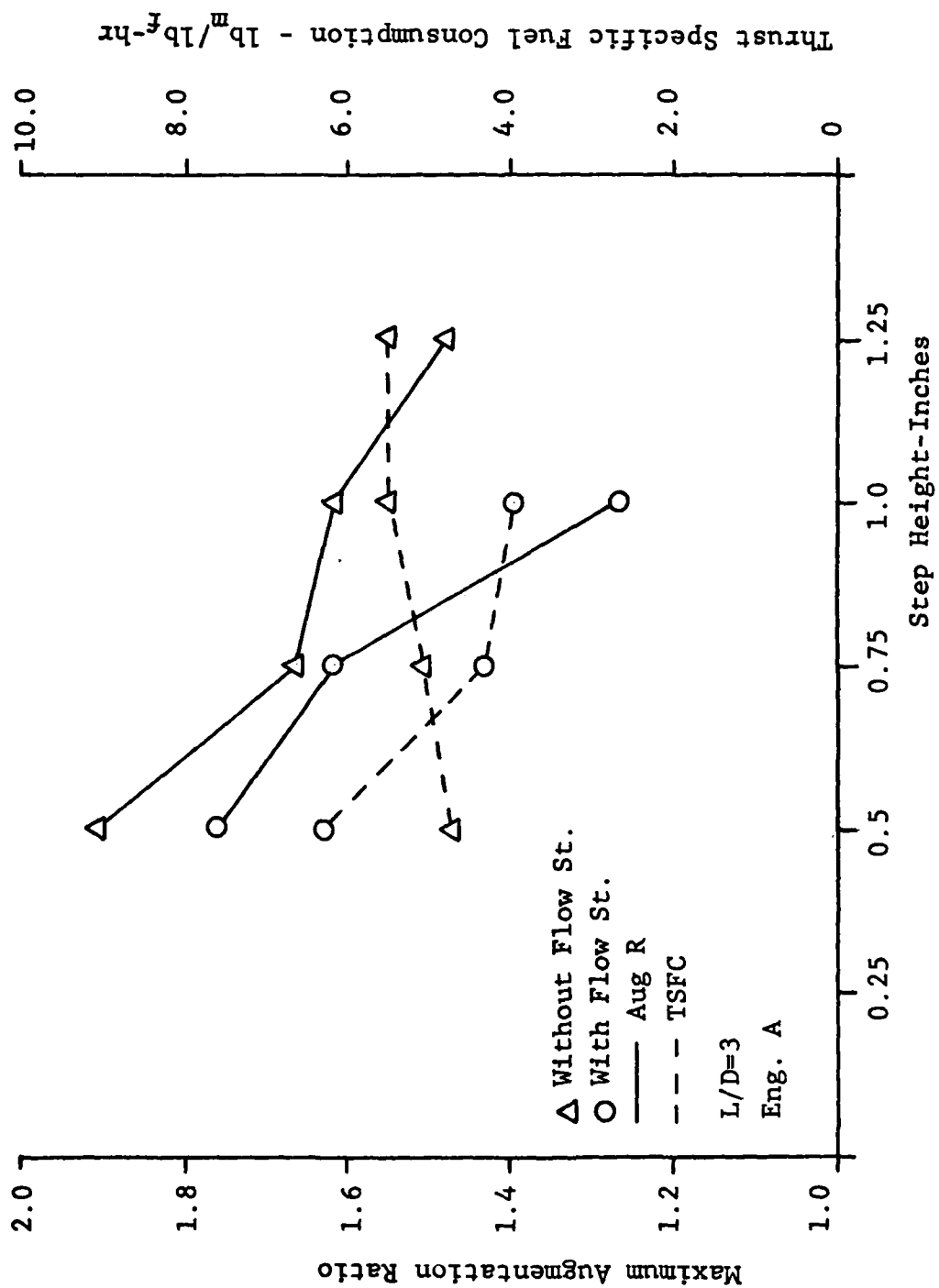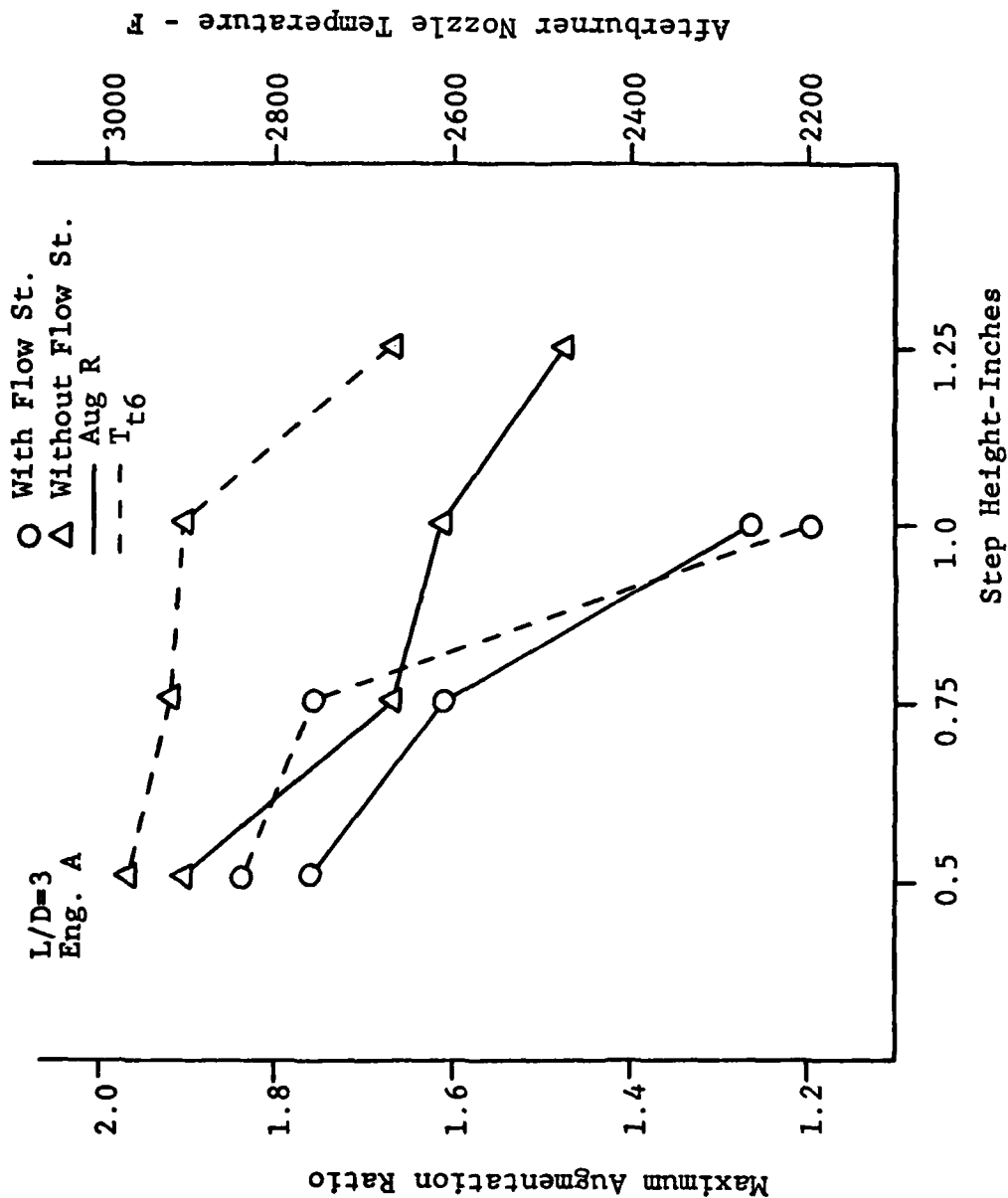Fig. 18 Effect of Step Height on Maximum Augmentation Ratio and T_{t6} With and Without Flow Straighteners

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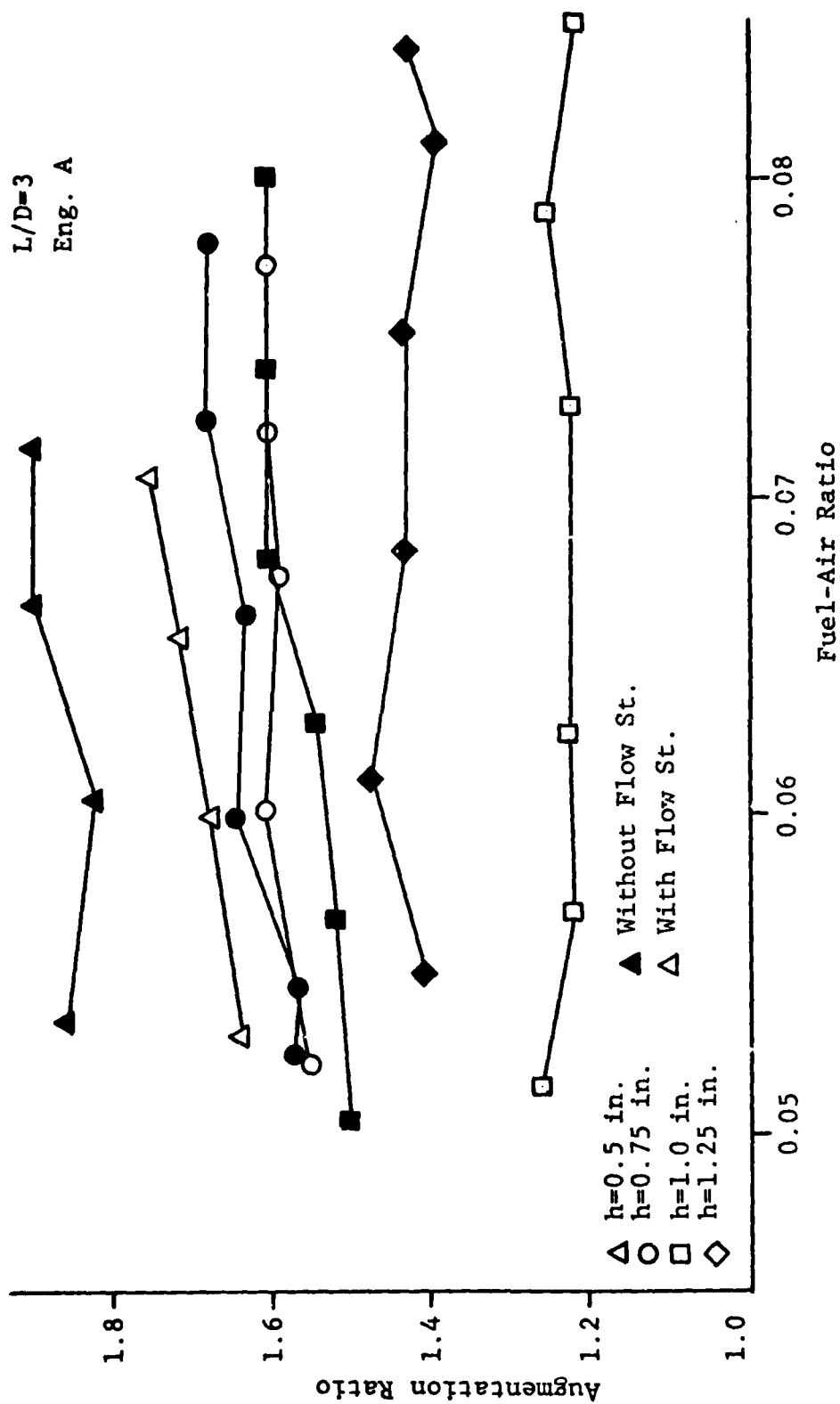
Fig. 19 Effect of Fuel-Air Ratio Changes on Augmentation
Ratio, With and Without Flow Straighteners

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decrease in fuel flow accompanied by a small increase in thrust as step height is increased. This could suggest a slightly improved combustion source, however, the net effect from the standpoint of augmentation ratio and thrust is still decreased performance.

Effects of Flameholders

Performance of the Y-shaped, V-gutter flameholders was consistent with the results obtained by Barham. For different blockages and configurations, the augmentation ratio remained approximately the same, however, thrust was lower and TSFC higher. This, as found by Barham, suggests that blockage drops the mass flow to the engine.

Figure 20 shows a typical plot of how the flameholder performed compared to the "clean" configuration at h=0.75 inches. Additional graphs were deemed unnecessary since the data merely confirmed past results.

As a point of interest however, a circular flameholder (unlike that used by Barham) was constructed to see what effect it might have in the swirling turbine exhaust flow environment. As Fig. 20 suggests, it provided better augmentation ratios than either of the other two configurations plotted. Although absolute thrust was less than the "no blockage" configuration, thrust performance at minimum A/B was only three pounds less than the maximum "no blockage" thrust of 100 pounds. This equates to a 3% loss
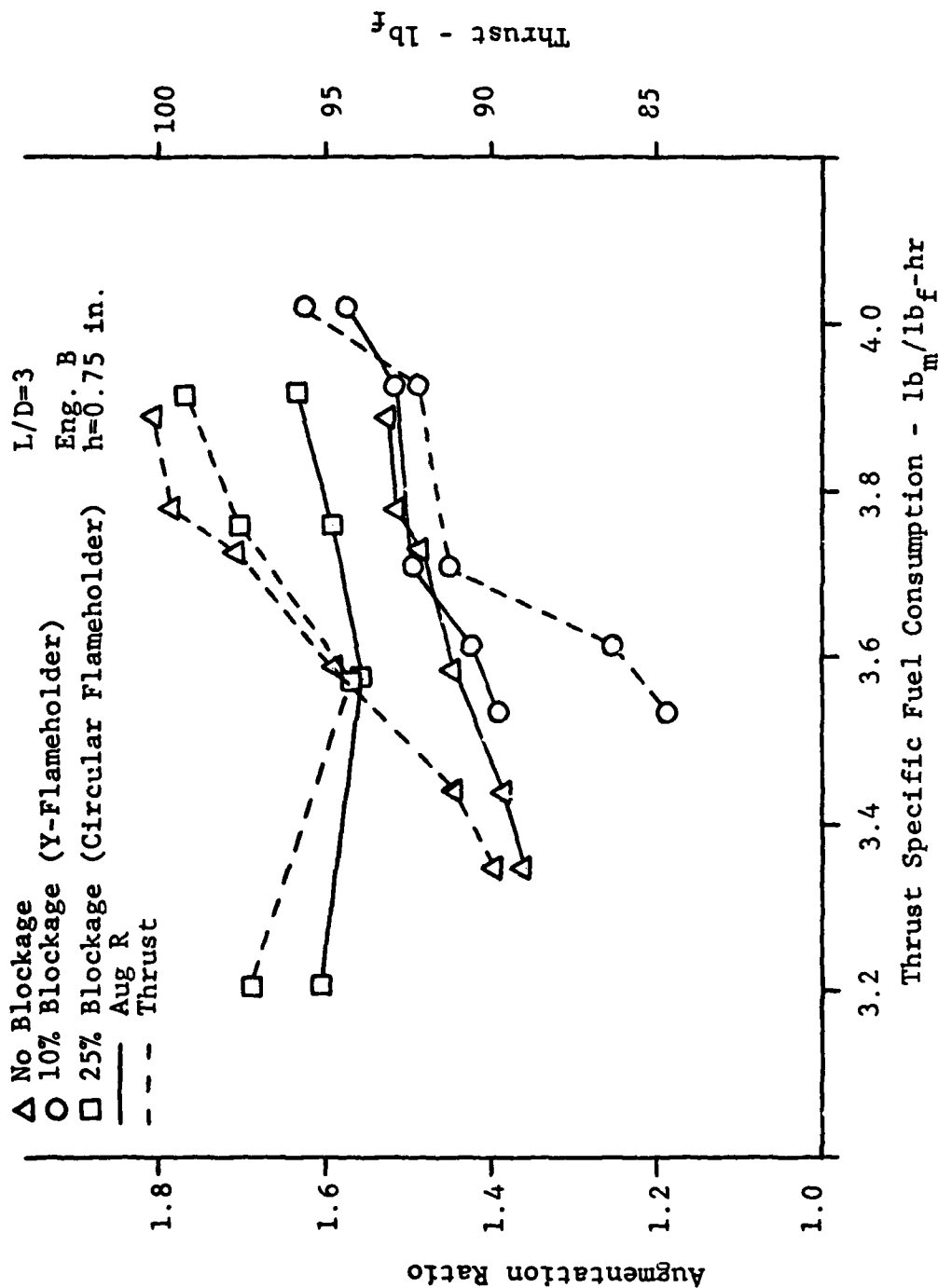
Fig. 20 Effect of Y-Shaped and Circular Flameholders on Augmentation Ratio, Thrust, and TSFC

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in thrust, but is accompanied by an 18% savings in TSFC. The reduction in TSFC probably results from better mixing due to enhancement of the recirculation zone, and thereby an improvement in the combustion process.

V. Conclusions and Recommendations

As a result of this investigation, it was shown that step height is a contributing factor in the performance of a sudden expansion afterburner as suggested by Ref. 3. Flow straighteners and Y-shaped flameholders were shown detrimental to performance; therefore the following specific conclusions were made.

Conclusions

The conclusions stated here are based on test results realizing the connection between diffuser length (which may affect fuel vaporization) and A/B performance is not taken into account.

1. A step height of 0.5 inch provides greater performance values and the best thermal efficiency for the engine/afterburner combination studied.

2. Flow straightening of the turbine exhaust swirl is not beneficial. Allowing the flow to swirl naturally provides better combustion and greater overall performance.

3. Flameholders in general produce a reduction of mass flow and thus a decrease in performance. However, annular V-gutter flameholders of proper design may significantly improve TSFC without a sacrifice in thrust.

4. Augmentation ratio and thrust do not vary significantly over the A/B operating range.

Recommendations

1. An afterburner fuel ring should be mounted at the step position of each diffuser and then run to see what effect diffuser length has on fuel vaporization.

2. An attempt should be made to shorten diffuser lengths by increasing the wall angle, holding step height constant.

3. Values of h near 0.5 inch could be investigated to determine where the optimum is located.

4. The circular flameholder described earlier should be investigated as a possible way to achieve reasonable thrust levels at lower fuel consumption rates. It could also be studied in connection with recommendation 2.

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Appendix A

Data Reductions

Data for this investigation reduced in the same general way as that used by Wolfe and Barham.

Recorders

A Honeywell 906B Visicorder was used to record various pressures, temperatures, and thrust. Table I shows the appropriate scale factors used on the visicorder and on which side the zero setting was located. Prior to calibration, all channels except 6 and 10 (T_{t6} and T_3) were zeroed on the appropriate side. Channels 6 and 10 were set to control room temperature.

Table I
Scale Factors

Quantity	Channel	Zero Setting	Scale Factor
T_{t6}	5	C/R Temp-Left	800F/inch
P_3	7	Right	8psi/inch
P_4	8	Left	5 psi/inch
P_5	9	Right	10 psi/inch
T_3	10	C/R Temp-Left	100F/inch
F	11	Right	25lb/inch
P_{t5}	12	Right	5psi/inch

Main engine and afterburner fuel flows were recorded on
a Honeywell Chart Recorder Model SY 153X(28). This unit
contained a frequency-to-voltage converter for each channel
and displayed frequency as a linear output deflection
proportional to the input frequency. The actual fuel flow
was then computed using the formula given under the section
titled Fuel Flow Rate.

Air Flow Rate

Air flow rate was determined by manually recording
the ΔP measurement in inches of water directly from the
water manometer. This measurement was then converted to
mass flow by using the Bellmouth curve developed by Kent.
The mass flow was corrected to sea level standard conditions
by using the equation:

$$m_a = \bar{\dot{m}}_a \frac{\sqrt{\theta}}{\delta}$$

where

$$\theta = \frac{T_o}{519^\circ R}$$

and

$$\delta = \frac{P_o}{29.92 \text{ in Hg}}$$

Fuel Flow Rate

Fuel flow was calculated by measuring the pen deflec-
tion of the Honeywell recorder in percent and then inserting
that value into the following equations:

$$\bar{\dot{m}}_{fe} = (2.5 \times 10^{-4})(FF_e\% \times 3) \frac{SpGr}{0.75}$$

$$\bar{\dot{m}}_{ab} = (2.5 \times 10^{-4})(FF_{ab}\% \times 3) \frac{SpGr}{0.75}$$

where SpGr=fuel specific gravity.

The total uncorrected fuel flow was calculated using the equation:

$$\bar{\dot{m}}_{ft} = \bar{\dot{m}}_{fe} + \bar{\dot{m}}_{ab}$$

Sea level standard condition corrections were done by applying equation:

$$\dot{m}_{ft} = \frac{\dot{m}_{ft}}{\delta\sqrt{\theta}}$$

Fuel Air Ratio

The corrected values for fuel/air ratio were obtained by applying the simple equation:

$$f_t = \dot{m}_{ft}/\dot{m}_a$$

Compressor Pressure Ratio

The compressor pressure ratio was computed using the equation:

$$CPR = \frac{P_3 + P_o}{P_o}$$

where P_3 = compressor pressure in psig.

Thrust

Thrust was corrected to standard sea level conditions by using the equation:

$$F = \bar{F}/\delta$$

Thrust Specific Fuel Consumption

Corrected values of TSFC were obtained using the formula:

$$TSFC = (\dot{m}_{ft} \times 3600)/F$$

Specific Thrust

Specific thrust at standard sea level conditions was computed using:

$$F_{sp} = F/\dot{m}_a$$

RPM

RPM readings were obtained by manually recording the digital counter reading and multiplying it by a factor of 60 seconds/minute. It was then corrected to standard conditions by using the formula:

$$N = \bar{N}/\sqrt{\theta}$$

A/B Total Pressure Loss

Total pressure loss was calculated according to the following equation:

$$\% \text{ Loss} = \frac{(P_{t5} - P_{t6})}{P_{t5}} \times 100$$

Afterburner Thermal Efficiency

Thermal efficiency was estimated using the relationship:

$$n_T = \frac{(T_{t5} - T_{t6})_{act}}{(T_{t5} - T_{t6})_{ideal}}$$

which is found in Ref. 8. Because of low mach numbers in the engine A/B (Ref. 5), T_5 and T_6 were assumed close to T_{t5} and T_{t6} for the efficiency calculation. According to Ref. 8, T_{t5} actual is equal to T_{t5} ideal, therefore, the gage reading of T_5 was used for both. The T_6 visicorder reading was converted using the scale factor and used for T_{t6} actual. The value for T_{t6} ideal was chosen from Ref. 2, which gives adiabatic flame temperature based on fuel/air ratio and compressor discharge temperature, T_3.

Augmentation Ratio

It must be pointed out that augmentation ratio was calculated by dividing afterburner thrust by the thrust at MIL 1. It can also be calculated using MIL 2 values. This distinction must be kept in mind when comparing these results with other studies.

Vita

James A. Poier was born on ███████████████████

█████████████████████ He graduated from high school in
1960 and entered the University of Washington. Following
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uating in May, 1969. He served tours with the 335 Tactical
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from 1969 to 1972. Upon completion of his Korean tour, he
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from 1973 to 1975. In early 1975 he was assigned to the
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ing the School of Engineering, Air Force Institute of
Technology, in June, 1977.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation was made on the performance of a small turbojet/dump combustor afterburner combination as a function of varying afterburner step height, straightening of the exhaust flow swirl from the turbine exit, and installing flameholders of varying degrees of blockage. Results indicated that a step height of 0.5 inch provided the greatest increase in performance with respect to thrust, thrust specific fuel consumption, augmentation ratio, (CONT'D)

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(Cont'd from block 20) and specific thrust.

Performance was degraded in all cases when flow straighteners were used. Likewise, the addition of Y-shaped, V-gutter flameholders also degraded performance and in some cases made lighting the afterburner impossible. This result confirmed and expanded the data in reference 1. Comparing efficiencies tended to show decreasing efficiency with increasing step height.